MURI: Impact of Oceanographic Variability on Acoustic Communications

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LONG-TERM GOALS

Couple together analytical and numerical modeling of oceanographic and surface wave processes, acoustic propagation modeling, statistical descriptions of the waveguide impulse response between multiple sources and receivers, and the design and performance characterization of underwater acoustic digital data communication systems in shallow water.

OBJECTIVES

Develop analytical/numerical models, validated with experimental data, that relate short-term oceanographic variability and source/receiver motion to fluctuations in the waveguide acoustic impulse response between multiple sources and receivers and ultimately to the capacities of these channels along with space-time coding and adaptive modulation/demodulation algorithms that approach these capacities.

APPROACH

The focus of this research is on how to incorporate an understanding of short-term variability in the oceanographic environment and source/receiver motion into the design and performance characterization of underwater acoustic, diversity-exploiting, digital data communication systems. The underlying physics must relate the impact of a fluctuating oceanographic environment and source/receiver motion to fluctuations in the waveguide acoustic impulse response between multiple sources and receivers and ultimately to the channel capacity and the design and performance characterization of underwater acoustic digital data communication systems in shallow water. Our approach consists of the following thrusts.

1. Modeling short-term variability in the oceanographic environment.

The long-term (beyond scales of minutes) evolution of the physical oceanographic environment (e.g. due to currents and long period internal waves) imparts slow changes to the waveguide acoustic propagation characteristics. In contrast, surface waves driven by local winds and distant storms exhibit dynamics on much shorter scales (seconds to tens of seconds) and directly impact short-term acoustic fluctuations. In addition, shorter-period internal waves, finestructure, and turbulence also will contribute to propagation variability. An important question is the relative impact each of these has on short-term acoustic fluctuations. Here we will couple models of the background time-evolving

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14. ABSTRACT
Couple together analytical and numerical modeling of oceanographic and surface wave processes, acoustic propagation modeling, statistical descriptions of the waveguide impulse response between multiple sources and receivers, and the design and performance characterization of underwater acoustic digital data communication systems in shallow water.

15. SUBJECT TERMS

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oceanographic environment with models of the surface wave dynamics to provide realistic sound speed fields along with their spatiotemporal correlation structure.

2. Transformation of environmental fluctuations and source/receiver motion into waveguide acoustic impulse response fluctuations between multiple sources and receivers.

Both ray-based (Sonar Simulation Toolset and Bellhop) and full-wave (Parabolic Equation) propagation modeling methods will be used to transform simulated sound speed fields, surface wave dynamics, and source/receiver motion directly into dynamic acoustic pressure fields. A Monte Carlo approach will be used to simulate realistic time-varying impulse responses between multiple sources and receivers. As an alternative, adjoint methods quantify the sensitivity of the channel impulse response to oceanographic (and geometric) variability. The linear approximation inherent in the sensitivity kernel may be valid for only a limited dynamic range of the environmental fluctuations corresponding to just a few seconds at the frequencies of interest but might provide useful insight into the mapping between environmental and acoustic fluctuations and subsequently to estimating the environmentally-dependent acoustic channel capacity.

3. Spatiotemporal statistical descriptions of waveguide impulse response fluctuations.

Statistical descriptions summarizing the spatiotemporal relatedness of waveguide impulse response fluctuations provide insight into the influence of environmental dynamics and can be used for system design and performance evaluation purposes. The scattering function provides a useful description of the channel in time delay and Doppler. In addition to estimating the scattering function from ensembles of realizations of fluctuating impulse responses (either from realistic simulations or at-sea observations), we also will use the sensitivity kernel for the impulse response combined with the dynamics and statistics of the environmental fluctuations to estimate the scattering function.

4. Channel capacity and the design and performance characterization of underwater acoustic, diversity-exploiting, digital data communication systems.

Channel capacity sets an upper bound on the information rate that can be transmitted through a given channel. The capacity of the highly dispersive and fluctuating ocean environment cannot be derived in closed form but only simulated or derived from measurements. In addition, realistic (constrained) capacity bounds will be derived that include practical implementation issues such as those imposed by phase-coherent constellations and realizable equalization schemes. Based on multiple source and receiver channel models developed from measured waveguide characteristics, we will assess the capacity of underwater acoustic channels and these will serve as goals for the design of space-time coding techniques and adaptive modulation/demodulation algorithms. An especially challenging problem in multipath-rich waveguides is the design of coherent communication schemes between moving platforms.

5. Benchmark simulations and validating experimental data.

A set of benchmark simulation cases will be defined for use in exploring transmitter/receiver design and performance characterization in the deployment of diversity-exploiting digital data telemetry systems (point-to-point and networked). Both fixed-fixed (stationary) and moving source and/or receiver scenarios will be considered across bands of frequencies in the range 1-50 kHz. Multiple source and receiver cases (MIMO) will be of particular interest. Validating experimental data will be

obtained during the ONR acoustic communications experiment in summer 2008 and other follow-on experiments to be scheduled in the future.

To address the issue of underwater acoustic digital data communication in a fluctuating environment, we have brought together a multidisciplinary research team consisting of oceanographers, ocean acousticians, and signal processors. Team members consist of faculty and researchers from four universities and unfunded collaborators from private industry and a navy laboratory:

- University of California, San Diego (UCSD) - W.S. Hodgkiss, W.A. Kuperman, H.C. Song, B.D. Cornuelle, and J.G. Proakis

- University of Washington (UW) - D. Rouseff and W. Fox

- University of Delaware (UDel) - M. Badiey and J. Kirby

- Arizona State University (ASU) - T. Duman

- Heat, Light, and Sound (HLS) - M. Porter, P. Hursky, and M. Siderius

- SPAWAR Systems Center – San Diego (SSC-SD) – V.K. McDonald and M. Stevenson

WORK COMPLETED

A shallow water acoustic communications experiment (KAM08) was conducted early summer 2008 off the western side of Kauai, Hawaii. Both fixed and towed source transmissions were carried out to multiple receiving arrays over ranges of 1-8 km. Substantial environmental data was collected including water column sound speed structure (CTDs and thermistor strings), water column current structure (ADCP), sea surface directional wave field (waverider buoy), and local wind speed and direction.

Publications related to this MURI include [1-6].

RESULTS

The Kauai Acomms MURI 2008 (KAM08) Experiment was conducted in shallow water (20 m – 600 m) off the western side of Kauai, Hawaii, at the Pacific Missile Range Facility (PMRF) over the period 16 June – 2 July 2008. The objective of KAM08 was to collect acoustic and environmental data appropriate for studying the coupling of oceanography, acoustics, and underwater communications. The focus was on fluctuations over scales of a few seconds to a few tens of seconds that directly affect the reception of a data packet and packet-to-packet variability.

A set of mooring locations were defined with PMRF. These are shown in Fig. 1 adjacent to the 100 m isobath along with the deployment positions of the acoustic sources, receiving arrays, and environmental moorings. For extended periods of time, the R/V Melville used dynamic positioning for deployment of a large-aperture, 8-element source array at Sta00. In addition, a near-seafloor source was deployed at Sta05. A small-aperture, near-seafloor vertical receive array was deployed at Sta02 and two large-aperture, vertical receive arrays were deployed at Sta08 and Sta16. Environmental moorings deployed included a thermistor string at Sta03 and a waverider buoy at Sta06. Also, self-

recording thermistors were attached to the receive arrays at Sta08 and Sta16. In addition to the fixed-source transmissions, source tows were carried out in the area. These included tows close to and parallel to the moorings as well as upslope/downslope tracks perpendicular to the moorings that covered water depths from 20 m to 600 m. Most source transmissions were in the 12-20 kHz band and included both environmental probing waveforms as well as communication transmissions.

An example of the dynamic water column environment during KAM08 is shown in Fig. 2. While always downward-refracting, the mixed layer depth changes from as little as 20 m to as much as 60 m or more over the course of 24 hours. Similarly, the wind speed and sea surface conditions exhibited a daily pattern. Fig. 3 shows wind speed and direction data along with waverider-derived sea surface wave spectra.

The channel impulse response (CIR) was estimated using various waveforms (e.g. FM chirps and MLS sequences). An example of the CIR from the deepest source array transducer at Sta00 to the large-aperture vertical receive array at Sta08 4 km away is shown in Fig. 4.

Examples of the short-term fluctuations in the observed channel impulse response (CIR) over the 4 km transmission path from the deepest source array transducer at Sta00 to the vertical receive array at Sta08 are provided in Fig. 5. These correspond to a 9 s duration time interval (vertical axis) with the CIR delay spread being on the order of a few tens of ms (horizontal axis). The upper element has a longer duration CIR that fluctuates rapidly while the deeper elements have shorter duration CIRs that appear to be more stable although still varying over the observation interval.

IMPACT / APPLICATIONS

Acoustic data communications is of broad interest for the retrieval of environmental data from in situ sensors, the exchange of data and control information between AUVs (autonomous undersea vehicles) and other off-board/distributed sensing systems and relay nodes (e.g. surface buoys), and submarine communications.

RELATED PROJECTS

In addition to other ONR Code 321OA and Code 321US projects investigating various aspects of acoustic data communications from both an ocean acoustics and signal processing perspective, a second MURI also is focused on acoustic communications (J. Preisig, “Underwater Acoustic Propagation and Communications: A Coupled Research Program”).

PUBLICATIONS

[1] A. Song, M. Badiey, H.C. Song, W.S. Hodgkiss, M.B. Porter, and the KauaiEx Group, “Impact of ocean variability on coherent underwater acoustic communications during the auai experiment (KauaiEx),” J. Acoust. Soc. Am. 123(2): 856-865, DOI: 10.1121/1.2828055 (2008). [published, refereed]

[2] A. Song, M. Badiey, and V. K. McDonald, “Multichannel combining and equalization for underwater acoustic MIMO channels”, Proc. Oceans’08, Quebec, Canada, Sept. 15-Sept 18, 2008. [published]

[3] K. Raghukumar, B.D. Cornuelle, W.S. Hodgkiss, and W.A. Kuperman, “Pressure sensitivity kernels applied to time-reversal acoustics,” J. Acoust. Soc. Am. 124(1): 98-112, DOI: 10.1121/1.2924130 (2008). [published, refereed]

[4] M. Siderius and M.B. Porter, "Modeling broadband ocean acoustic transmissions with time-varying sea surfaces," J. Acoust. Soc. Am. 124(1): 137-150, DOI: 10.1121/1.2920959 (2008). [published, refereed]

[5] P. Roux, B.D. Cornuelle, W.A. Kuperman, and W.S. Hodgkiss, “The structure of ray-like arrivals in a shallow water waveguide,” J. Acoust. Soc. Am. (in press, 2008). [in press, refereed]

[6] D. Rouseff, M. Badiey, and A. Song, "Effect of reflected and refracted signals on coherent underwater acoustic communication: Results from KauaiEx 2003," J. Acoust. Soc. Am. (submitted, 2008).

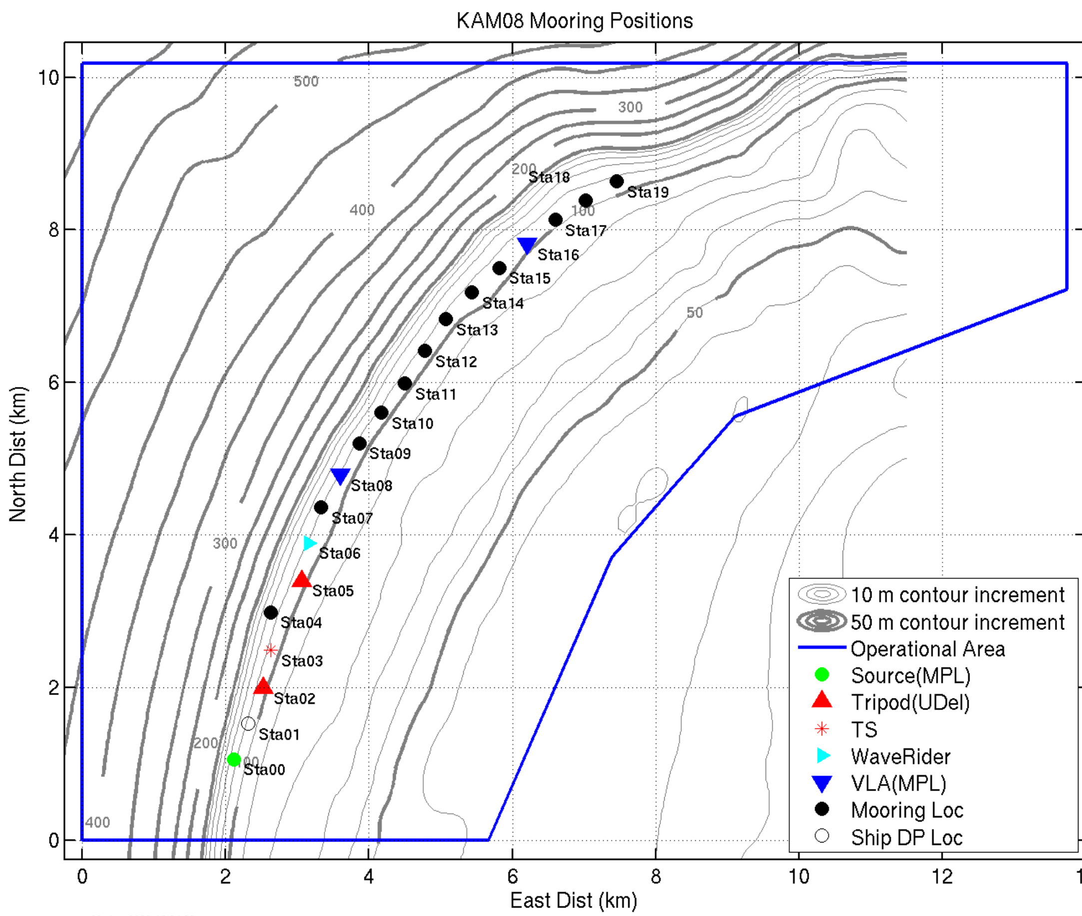

Figure 1. Mooring deployment positions in km with respect to southwest corner of the operational area (22°06.5’ N, 159°50’W). Sta00 is the ship dynamic positioning location during deployment of the source array. In addition, a fixed source was deployed at Sta05. Receiving arrays were deployed at Sta02, Sta08, and Sta16. A thermistor string was deployed at Sta03 and the waverider buoy was deployed at Sta06.

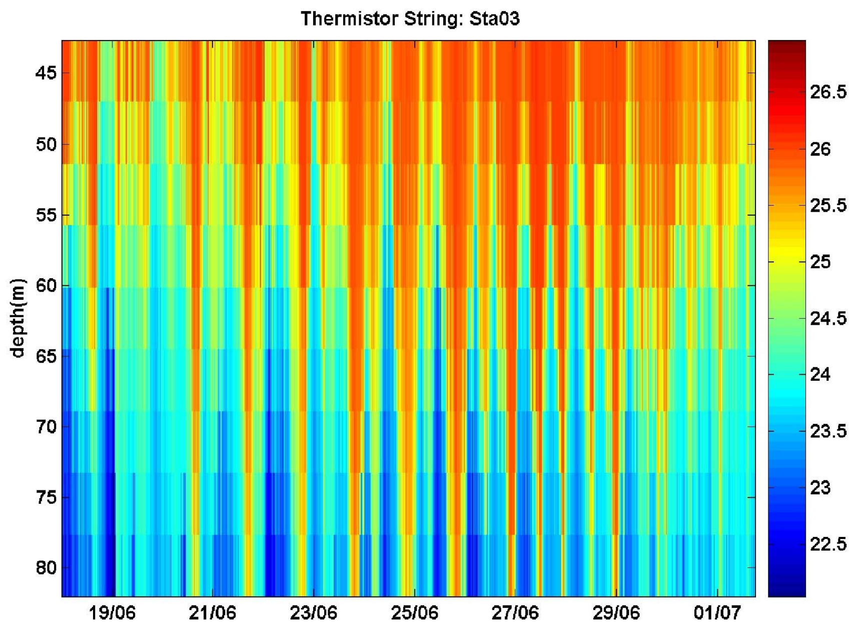

Figure 2. Water column temperature structure recorded by the thermistor string moored at Sta03.

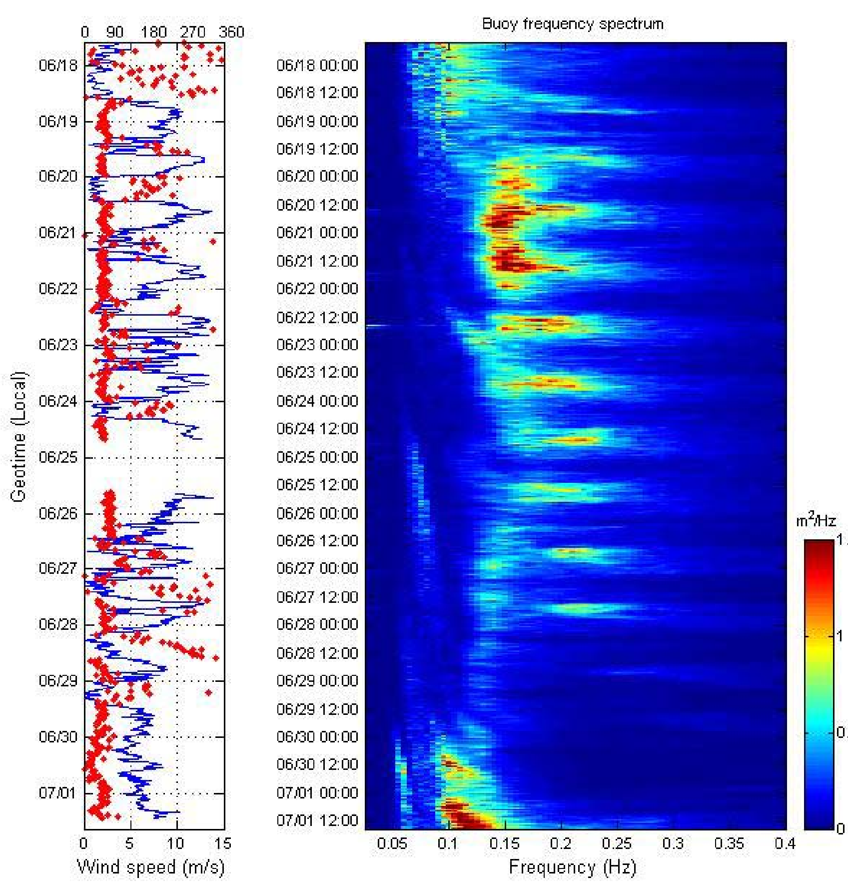

Figure 3. Ship wind speed and direction data along with waverider derived sea surface wave spectra.

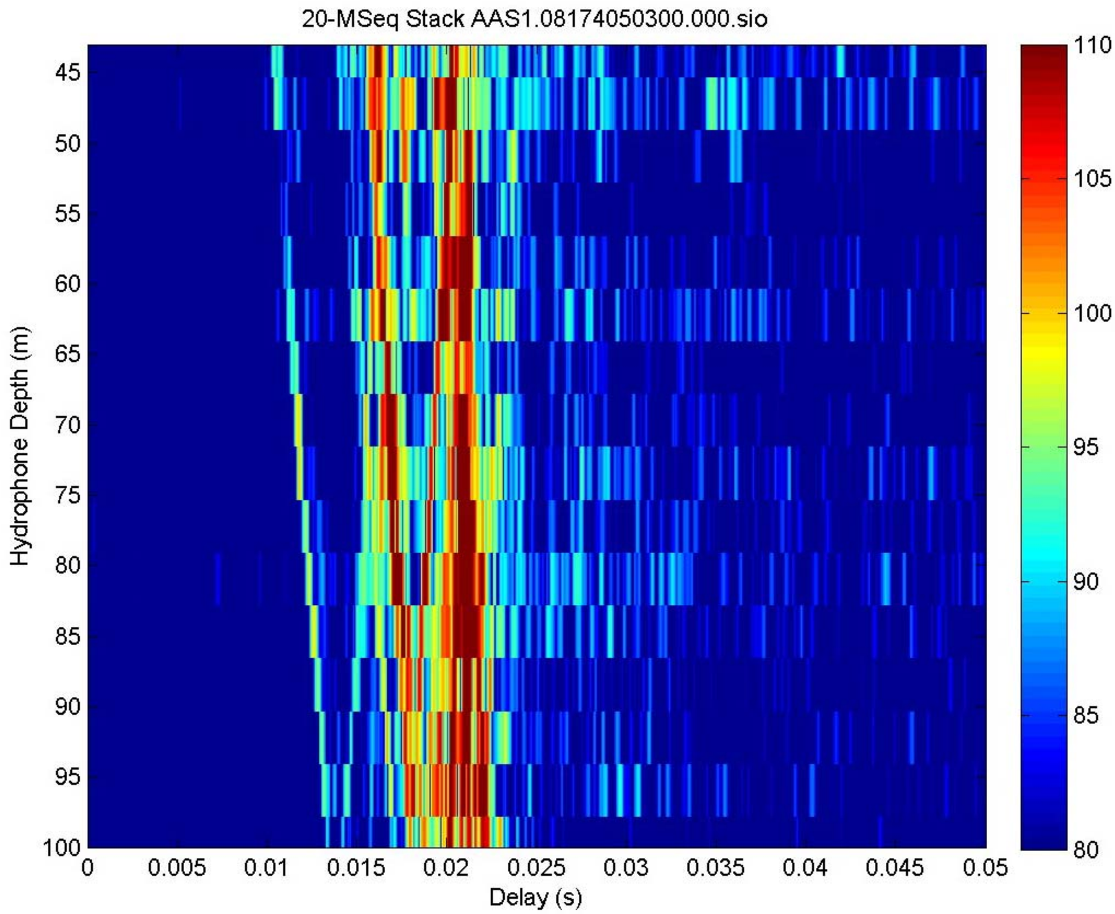

Figure 4. Channel impulse response. Deepest source array transducer to vertical receive array at Sta08 (range 4 km). Coherent integration of 20 MLS transmissions.

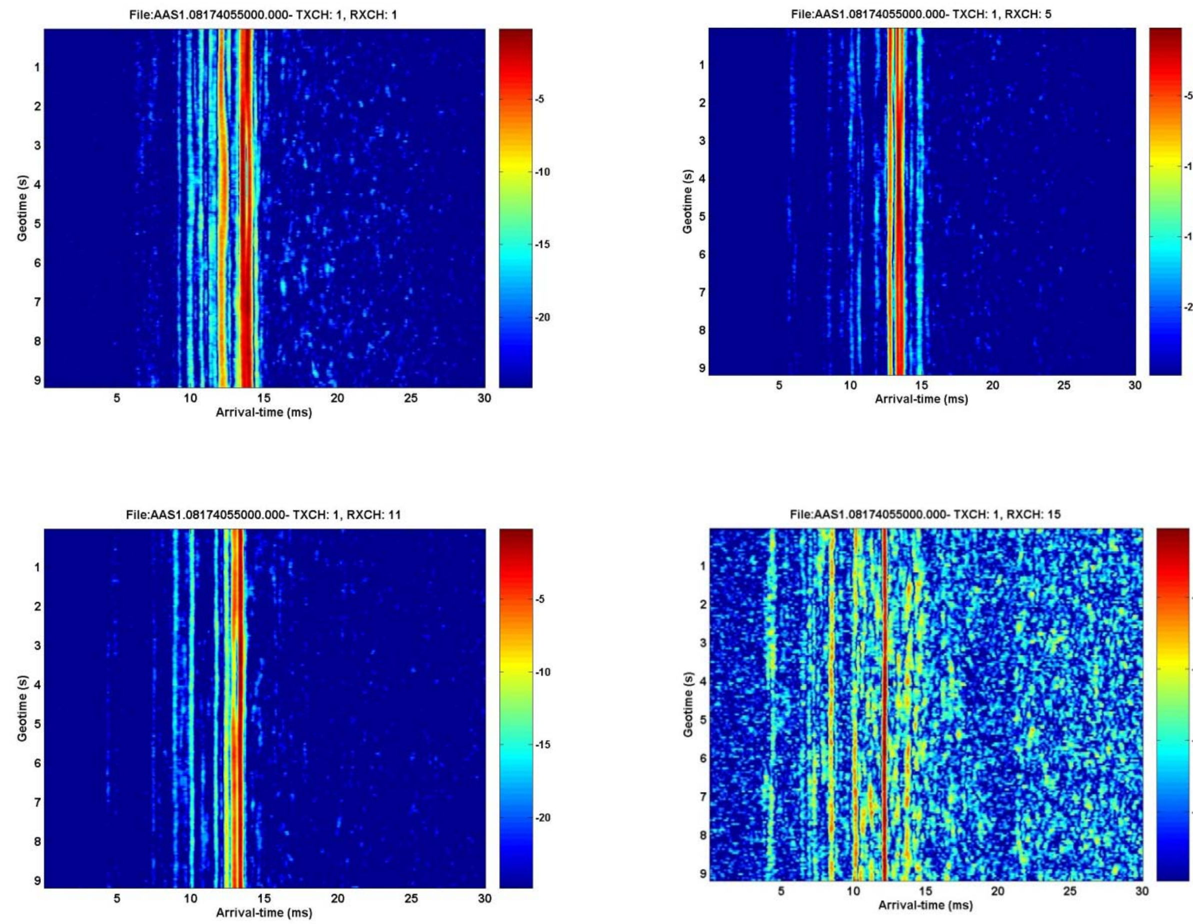

Figure 5. Channel impulse response at Sta08. The depths of vertical receive array CH-1, CH-5, CH-11, and CH-15 were 95.25m, 80.25m, 57.75m, and 42.75m, respectively. A BPSK sequence with R = 4 kilosymbols/s and f_c = 16 kHz was used for channel estimation. The transmission was from the deepest source array transducer at 82.5 m depth. The source / receive array range was 4 km.